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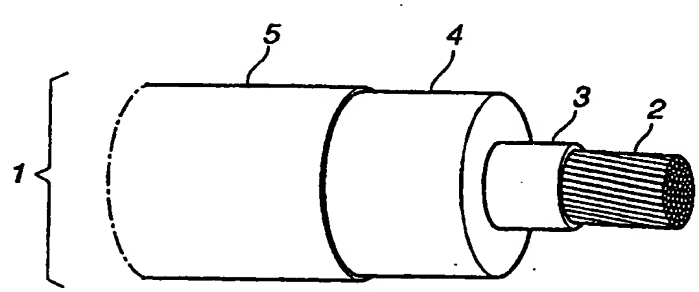

(57) Abstract

The present invention relates to installations for transformerless generation of HVDC and wherein the installation comprises rotating high-voltage single-winding/multiple-winding machines and converters. The single-winding/multiple-winding machine comprises a magnetic circuit with one or more magnetic cores and one or more windings, phase-shifted in space, which comprise a cable with one or more current-carrying conductors (2), each conductor comprising a number of strands, around each strand there being arranged an inner semiconducting layer (3), around which is arranged an insulating layer (4) of solid insulation, around which is arranged an outer semiconducting layer (5).

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ROTATING ELECTRICAL MACHINE PLANTS

TECHNICAL FIELD

The present invention relates to installations for transformerless generation of HVDC (high-voltage direct current) and wherein the installation comprises a rotating high-voltage single-winding or multiple-winding machine and a converter. The invention also comprises devices for high-voltage electric machine operation with a variable speed. In practice, this means that the installations convert a mechanical torque into direct current and direct voltage without intermediate transformers, and that the installations convert direct current and direct voltage into mechanical torque without intermediate transformers.

The single-winding or multiple-winding machine comprises a magnetic circuit with one or more cores of laminated, normal or oriented, sheet or other, for example amorphous or powder-based, material, or any other action for the purpose of allowing an alternating flux, one or more winding systems, cooling systems, etc., which may be disposed in the stator or the rotor of the machihe, or in both.

The single-winding or multiple-winding machine may also be made as an air-gap-wound machine without magnetic material or with magnetic material only in the back portion.

The invention also comprises methods for manufacturing magnetic circuits for a rotating high-voltage single-winding/multiple-winding machine.

BACKGROUND ART, THE PROBLEM

As mentioned under the "Technical Field", devices according to the invention are primarily intended to be part of installations for transformerless generation of high-voltage direct current and for high-voltage electric machine drives. Installations where the invention will be used normally lie within the power range of 1 MW to 15 GW and comprise one or several rotating machines.

Within electronic power engineering there is a technical field which is currently referred to as power electronics. This expression corresponds to the German "Leistungselektronik" and is sometimes still called "Stromrichtertechnik" in German. The field comprises conversion of electric power between different forms, such as conversion between

- DC and AC, inverter operation
- AC and DC, rectifier operation

AC and AC corresponds to ac conversion/ac conversion with an arbitrary ratio between the frequency, amplitude, phase position and phase number of the voltages,

DC and DC corresponds to dc conversion/dc conversion.

The terminology in this field is unfortunately not quite consistent. However, an IEC summary is to be found in "International Electrotechnical Dictionary" and in Publ. IEC 60050-551 IEV, "Power electronics".

There are a very large number of different semiconductor components which may be included in the fields of use which are comprised by the patent application. One example of the state of the art in this respect is found in "Modern Power Electronics" by Bose et al, IEEE Industrial Electronics Society, ISBN:0-87942-282-3. Among the components mentioned there are:

- thyristors, diodes, triacs, gate turn-off thyristors (GTO), bipolar transistors (BJT), PWM transistors, MOSFET, insulated gate bipolar transistors (IGBT), static induction transistors (SIT), static induction thyristors (SITH), MOS-controlled thyristors (MCT), etc.

Semiconductor connections for inverter operation and rectification are commonly referred to in English as "converters". No unambiguous Swedish correspondence exists. Since that part of the invention which deals with HVDC power conversion comprises both inverter operation and rectifier operation, the semiconductor connections under discussion will be referred to below as converters.

For that part of the invention which deals with high-voltage electric machine drive with a variable speed, the above-mentioned AC/AC power conversion will be used. Such electric machine drive will be described

below both with regard to the state of the art and with regard to the application according to the invention.

To be able to describe both the technical and economic advantages and the gains derived by using devices according to the invention, a description will be given both of how installations for generation of HVDC and for high-voltage electric machine drive with a variable speed are designed according to the state of the art.

A conventional HVDC transmitter station is clear from Figure 1. In principle, it comprises a number of ac generators G1---Gn which, according to the state of the art, have a voltage of 25-30 kV. Via transformers A1---An, preferably D/Y-connected, the generator voltage is stepped up to a suitable ac transmission level and is transmitted over shorter of longer distances via ac transmission lines in a high-voltage ac network. The predominant method for rectification is then to use so-called 12-pulse rectification. The sine shape in the ac network is secured with ac filters near the converters. The 12-pulse rectification assumes that consecutively series-connected converter bridges B1---Bn are fed from ac systems which are displaced 30 electrical degrees relative to each other. This is achieved by connecting to the high-voltage ac network Y/Y-connected converter transformers Y1---Yn and corresponding Y/D-connected converter transformers D1---Dn, which are allowed to feed the converters.

Such a conventional HVDC transmitter station thus comprises two transformer stages, ac filters, ac circuit breakers and an ac busbar system. Because the transformers are normally intended for transmission of high powers, they are normally oil-cooled and oil-insulated. Because of the series-connected converters, the windings and the bushings of the converter transformers will be subjected to a rising dc potential, counting from ground. It places very heavy demands on the insulation and the bushings of these transformers. This is describes, inter alia, in "Power Transmission by Direct Current" by E. Uhlmann, Springer Verlag 1975, pp. 327-328, in ELECTRA No. 141, April 1992, pp. 34-39, and in ELECTRA No. 155, Aug. 1994, pp. 6-30.

An HVDC transmission according to the one described above is described, inter alia, in an article entitled "The Skagerack transmission" - The world's longest HVDC submarine cable link" in Asea Journal 1980, Vol. 53, Nos. 1-2, pp. 3-12, and in an article "Direct connection of generators to HVDC converters" in ELECTRA No. 149, August 1993.

Recently, an embodiment of an HVDC transmitter station has been discussed which comprises direct connection from each generator to the Y/Y-connected and the Y/D-connected converter transformers. Such an installation is described, inter alia, in the above-mentioned article in ELECTRA and is here referred to as a "direct connection".

Such a connection is clear from Figure 2. The voltage from the generators G1---Gn is here fed directly to the converter transformers Y---Yn and D1---Dn, respectively. Such a connection makes greater demands on the converter transformers since they must now also be responsible for the step-up transformation of the voltage of the generators to the level corresponding to the desired direct-voltage level.

One problem with such a connection is that converter harmonics may give increased losses in the stator windings of the generators.

To distinguish the present invention from the prior art, it will be especially pointed out that the "HVDC converter" referred to in the above-mentioned article in ELECTRA Nol 149 for direct connection to the generators comprise the two Y/Y-connected and Y/D-connected converter transformers, respectively, and the converters.

There is a special interphase transformer converter connection, which is shown in Figure 3. In conformity with Figures 1 and 2, the supply of the converters S1 and S2 takes place by means of two three-phase voltages, displaced by 30 electrical degrees relative to each other, via the transformers T1 and T2. If the connection otherwise comprises the reactors R1 and R2, no dc potential stress arises on the feeding transformers or generators. R1 and R2 are often designed with a common core and winding as well as a centre tap.

In the introductory part of the specification it was mentioned that a device according to the invention comprises a single-winding/multiple-winding machine. One example of a multiple-winding machine according to the state of the art is described in US 4,132.914 entitled "Six-phase winding of electric machine stator". The windings are here especially formed to obtain as low voltages as possible between the external connections. The six-phase windings in this and similar machines are formed as two three-phase windings which are normally electrically displaced relative to each other by 30 electrical degrees. This permits a possibility of subsequently achieving one single three-phase voltage with the aid of a Y-connected and a D-connected transformer.

The above-mentioned machine and similar machines according to the state of the art are designed for voltages of up to about 25 kV. Machines with two three-phase windings, electrically displaced relative to each other by 30 electrical degrees, may be used according to the above, without intermediate transformers, for 12-pulse rectification with converters. With the highest voltage in existing machines, however, the rectified voltage may amount to a maximum of about 30 kV, symmetrically distributed as about +/- 15 kV around ground potential.

Series connection of converters fed from several generators for achieving what is commonly termed HVDC, that is, direct voltages of 100 kV and higher, is not possible with generators according to the current technique with mica-based insulation technique because these do not withstand the dc component to which the generator windings in the most commonly used converter connections will be subjected.

A rotating high-voltage single-winding/multiple-winding machine included in an installation according to the invention is able to operate as a variable-speed motor fed via semiconductor connections from a high-voltage dc network and as a generator to generate an ac network via semiconductor connections and transformers.

Electric machine drives with variable speed for ac machines according to the state of the art assumes, for various practical reasons, that the machine is provided with two three-phase windings displaced relative to each other by 30 electrical degrees. For the speed control, the machines

then have to be supplied with a variable frequency. The voltage level of the supply according to the state of the art is of the order of magnitude of 5 kV.

Motor drives of the above-mentioned kind are published in a number of pamphlets and articles, such as in "High-speed synchronous motors. Adjustable speed drives", Asea pamphlet OG 135-101E, "Freqsyn - a new drive system for high-power applications", Asea Journal 59 (1986):4, pp. 16-19. An order for 100-MW adjustable-speed motors for driving a wind tunnel fan has been placed by NASA according to ABB Review 9/1995, p. 38.

The supply of such motor drives may take place in different ways, for example as a pure AC/AC power conversion or from a direct-voltage network via controllable converters. The construction of such an installation is described, inter alia, in an article entitled "Synchronous machines with single or double 3-phase star-connected winding fed by 12-pulse load commutated inverter", published in ICEM 94, International Conference on Electrical Machines, Part Vol. 1, pp. 267-272.

Electric machine drives with a variable speed may also be achieved with machines with a winding system if the supply takes place while utilizing the latest technical development, so-called PWM technique, that is, with pulse-width modulation and self-commutated converters, in which case also a six-pulse connection may be used.

Regarding somewhat smaller rotating electric machines, the so-called reluctance machines may be mentioned, which are currently designed for up to a few hundred kilowatts, wherein both the stator and the rotor are provided with salient poles. Such motors are described, inter alia, in "Variable speed switched reluctance motors" in IEE Proc. B, Vol. 127, Nov. 1980, pp. 253-265. The machines are currently low-voltage machines and the windings surround the salient poles of the stator in many layers. These reluctance machines are examples of machines which may be further developed for connection via converters to high dc voltage.

As will have been clear from the above, the present invention comprises a rotating high-voltage single-winding/multiple-winding machine intended for voltage levels significantly exceeding those which apply to machines

according to the state of the art. This also entails great possibilities for electric machine drives with variable speed at considerably higher voltage levels and the advantages this brings with regard to machine power etc.

To be able to describe the advantages and the inventive step which the invention represents, a description will first be made of the composition of such machines according to the state of the art. The single-winding/multiple-winding machine according to the invention relates to a machine which is capable of generating a voltage system or several voltage systems, phase-shifted in space, with a corresponding winding system. In all essentials, the composition of the rotating high-voltage single-winding/multiple-winding machine according to the invention is independent of whether the machine is made as a single-winding machine or whether it is made as a multiple-winding machine and whether it is used for HVDC generation or for high-voltage variable-speed motor drives.

The state of the art will therefore be described starting from a conventional single-winding machine with a voltage level of about 25-30 kV exemplified on the basis of a synchronous machine. The description substantially relates to the magnetic circuit of such a machine and how this is composed according to classic technique. Since the magnetic circuit referred to in most cases is disposed in the stator, the magnetic circuit below will normally be described as a stator with a laminated core, the winding of which will be referred to as a stator winding, and the slots in the laminated core for the winding will be referred to as stator slots or simply slots.

Most synchronous machines have a field winding in the rotor, where the main flux is generated by direct current, and an ac winding in the stator. The synchronous machines are normally of three-phase design. Sometimes, the synchronous machines are designed with salient poles. The latter have an ac winding in the rotor. Sometimes, the machines are designed with polyphase windings both in the stator and in the rotor as so-called synchronous flux machines to allow operation at other than synchronous speeds.

The stator body for large synchronous machines is often made of sheet steel with a welded construction. The laminated core is normally made from varnished 0.35 or 0.5 mm electric sheet. For larger machines, the sheet is punched into segments which are attached to the stator body by means of wedges/dovetails. The laminated core is retained by pressure fingers and pressure plates.

For cooling of the windings of the synchronous machine, three different cooling systems are available.

In case of air cooling, both the stator winding and the rotor winding are cooled by cooling air flowing through. The cooling air channels are to be found both in the stator laminations and in the rotor. For ventilation and cooling by means of air, the laminated core at least for medium-sized and large machines is divided into stacks with both radial and axial ventilation ducts disposed in the core.
The cooling air may consist of ambient air but at powers exceeding 1 MW, a closed cooling system with heat exchangers is substantially used. Air is the substantial medium for hydrogenerators.

Hydrogen cooling is normally used in turbogenerators up to about 400 MW and in large synchronous condensers. The cooling method functions in the same way as in air cooling with heat exchangers, but instead of air as coolant there is used hydrogen gas. The hydrogen gas has better cooling capacity than air, but difficulties arise at seals and in monitoring leakage.

For turbogenerators in the power range of 500-1000 MW, it is known to apply water cooling of both the stator winding and the rotor winding. The cooling channels are in the form of tubes which are placed inside conductors in the stator winding.

One problem with large machines is that the cooling tends to become non-uniform and that, therefore, temperature differences arise across the machine.

The stator winding is disposed in slots in the laminated core. The slots normally have a cross section as that of a rectangle or a trapezoid. Each

winding phase comprises a number of series-connected coil groups and each coil group comprises a number of series-connected coils. The different parts of the coil are designated coil side for that part which is placed in the stator and coil end for that part which is disposed outside the stator. A coil comprises one or more conductors brought together in height and/or width. Between each conductor there is a thin insulation, for example epoxy/glass fibre. The coil is insulated against the slot with a coil insulation, that is, an insulation intended to withstand the rated voltage of the machine to ground. As insulating material, various plastic, varnish and glass fibre materials may be used. Usually, so-called mica tape is used, which is a mixture of mica and hard plastic, especially produced to provide resistance to partial discharges, which can rapidly break down the insulation. The insulation is applied to the coil by winding the mica tape around the coil in several layers. The insulation is impregnated, and then the coil side is painted with a coal-based paint to improve the contact with the surrounding stator which is connected to ground potential.

The conductor area of the windings is determined by the relevant current intensity and by the cooling method used. The conductor and the coil are usually formed with a rectangular shape to maximize the amount of conductor material in the slot. A typical coil is formed of so-called Roebel bars, in which certain of the bars may be made hollow for a coolant. A Roebel bar comprises a plurality of rectangular, parallel-connected copper conductors, which are transposed 360 degrees along the slot. Ringland bars with transpositions of 540 degrees and other transpositions also occur. The transposition is made to avoid the occurrence of circulating currents which are generated in a cross section of the conductor material, as viewed from the magnetic field.

In this context, it should also be pointed out that, in connection with converter operation, harmonics arise in the currents. These harmonics are not distributed uniformly over the rectangular cross section, which leads to skin effect and increased losses.

For mechanical and electrical reasons, a machine cannot be made in just any size. The machine power is determined substantially by three factors:

- The conductor area of the windings. At normal operating temperature, copper, for example, has a maximum value of 3-3.5 A/mm^2.
- The maximum flux density (magnetic flux) in the stator and rotor material.
- The maximum electric field strength in the insulating material, the so-called dielectric strength.

Polyphase ac windings are designed either as single-layer or two-layer windings. In the case of single-layer windings, there is only one coil side per slot, and in the case of two-layer windings there are two coil sides per slot. Two-layer windings are usually designed as diamond windings, whereas the single-layer windings which are relevant in this connection may be designed as a diamond winding or as a concentric winding. In the case of a diamond winding, only one coil span (or possibly two coil spans) occurs, whereas flat windings are designed as concentric windings, that is, with a greatly varying coil width. By coil width is meant the distance in circular measure between two coil sides belonging to the same coil, either in relation to the relevant pole pitch or in the number of intermediate slot pitches. Usually, different variants of chording are used, for example fractional pitch, to give the winding the desired properties. The type of winding substantially describes how the coils in the slots, that is, the coil sides, are connected together outside the stator, that is, at the coil ends.

Outside the stacked sheets of the stator, the coil is not provided with a painted semiconducting ground-potential layer of carbon-based paint. The coil end is normally provided with an E-field control in the form of so-called corona protection varnish intended to convert a radial field into an axial field, which means that the insulation on the coil ends occurs at a high potential relative to ground. This sometimes gives rise to corona in the coil-end region, which may be destructive. The so-called field-controlling points at the coil ends entail problems in the design of a rotating electric machine.

Normally, all large machines are designed with a two-layer winding and equally large coils. Each coil is placed with one side in one of the layers and the other side in the other layer. This means that all the coils cross each other in the coil end. If more than two layers are used,

these crossings render the winding work difficult and deteriorate the coil end.

During the last few decades, there have been increasing requirements for rotating electric machines for higher voltages than what has previously been possible to design and manufacture. The maximum voltage level which, according to the state of the art, has been possible to achieve for synchronous machines with a good yield in the coil production is around 25-30 kV.

Certain attempts to a new approach as regards the design of synchronous machines are described, inter alia, in an article entitled "Water-and-oil-cooled Turbogenerator TVM-300" in J. Elektrotechnika, No. 1, 1970, pp. 6-8, in US 4,429,244, "Stator of Generator", and in Russian patent document CCCP Patent 955369.

The water- and oil-cooled synchronous machine described in J. Elektrotechnika is intended for voltages up to 20 kV. The article describes a new insulation system consisting of oil/paper insulation, which makes it possible to immerse the stator completely in oil. The oil can then be used as a coolant while at the same time using it as insulation. To prevent oil in the stator from leaking out towards the rotor, a dielectric oil-separating ring is provided at the internal surface of the core. The stator winding is made from conductors with an oval hollow shape provided with oil and paper insulation. The coil sides with their insulation are secured to the slots made with rectangular cross section by means of wedges. As coolant oil is used both in the hollow conductors and in holes in the stator walls. Such cooling systems, however, entail a large number of connections of both oil and electricity at the coil ends. The thick insulation also entails an increased radius of curvature of the conductors, which in turn results in an increased size of the winding overhang.

The above-mentioned US patent 4,429,244 relates to the stator part of a synchronous machine which comprises a magnetic core of laminated sheet with trapezoidal slots for the stator winding. The slots are tapered since the need of insulation of the stator winding is smaller towards the interior of the rotor where that part of the winding which is located

nearest the neutral point is disposed. In addition, the stator part comprises a dielectric oil-separating cylinder nearest the inner surface of the core. This part may increase the magnetization requirement relative to a machine without this ring. The stator winding is made of oil-immersed cables with the same diameter for each coil layer. The layers are separated from each other by means of spacers in the slots and secured by wedges. What is special for the winding is that it comprises two so-called half-windings connected in series. One of the two half-windings is disposed, centered, inside an insulating sleeve. The conductors of the stator winding are cooled by surrounding oil. Disadvantages with such a large quantity of oil in the system are the risk of leakage and the considerable amount of cleaning work which may result from a fault condition. Those parts of the insulating sleeve which are located outside the slots have a cylindrical part and a conical termination reinforced with current-carrying layers, the duty of which is to control the electric field strength in the region where the cable enters the end winding.

From CCCP 955369 it is clear, in another attempt to raise the rated voltage of the synchronous machine, that the oil-cooled stator winding comprises a conventional high-voltage cable with the same dimension for all the layers. The cable is placed in stator slots formed as circular, radially disposed openings corresponding to the cross-section area of the cable and the necessary space for fixing and for coolant. The different radially disposed layers of the winding are surrounded by and fixed in insulating tubes. Insulating spacers fix the tubes in the stator slot. Because of the oil cooling, an internal dielectric ring is also needed here for sealing the oil coolant against the internal air gap. The disadvantages of oil in the system described above also apply to this design. The design also exhibits a very narrow radial waist between the different stator slots, which means a large slot leakage flux which significantly influences the magnetization requirement of the machine.

A report from Electric Power Research Institute, EPRI, EL-3391, from 1984 describes a review of machine concepts for achieving a higher voltage of a rotating electric machine for the purpose of being able to connect a machine to a power network without an intermediate transformer. Such a solution is judged by the investigation to provide good efficiency

benefits and great economic advantages. The main reason that it was considered possible in 1984 to start developing generators for direct connection to power networks was that at that time a superconducting rotor had been produced. The large magnetization capacity of the superconducting field makes it possible to use an air gap winding with a sufficient thickness to withstand the electrical stresses.

By combining the most promising concept, according to the project, of designing a magnetic circuit with a winding, a so-called monolith cylinder armature, a concept where two cylinders of conductors are enclosed in three cylinders of insulation and the whole structure is fixed to an iron core without teeth, it was judged that a rotating electric machine for high voltage could be directly connected to a power network. The solution meant that the main insulation had to be made sufficiently thick to cope with phase-to-phase and phase-to-ground potentials. Obvious disadvantages with the proposed solution are that, in addition to requiring a superconducting rotor, it requires a very thick insulation which increases the size of the machine. The coil ends must be insulated and cooled with oil or freons to control the large electric fields in the ends. The whole machine must be hermetically enclosed to prevent the liquid dielectric from absorbing moisture from the atmosphere.

When manufacturing rotating electric machines according to the state of the art, the winding is manufactured with conductors and insulation systems in several steps, whereby the winding must be preformed prior to mounting on the magnetic circuit. Impregnation for preparing the insulation system is preformed after mounting of the winding on the magnetic circuit.

SUMMARY OF THE INVENTION, ADVANTAGES

One object of the invention is to provide installations for transformerless generation of HVDC and that the installation includes a rotating single-winding/multiple-winding machine with such a high voltage that the transformer stages shown in Figures 1 and 2, with step-up transformation of the generator voltage first to ac transmission high voltage and the Y/Y-connected and Y/D-connected transformers,

respectively, for achieving 12-pulse rectification with converters, can be eliminated. Thus, the machine is intended, inter alia, to directly supply the converters with the high voltage which is needed for achieving an HVDC network. In this context, the difference with respect to the above-mentioned "Direct connection" described in ELECTRA should be noted. It is clear from the above, it is another object of the invention to provide installations for high-voltage variable-speed electric machine drives.

In practice, the above two objects mean that the installations convert a mechanical torque, via converters, to direct current and direct voltage without intermediate transformers, and that the installations convert direct current and direct voltage, via converters, to a mechanical torque without intermediate transformers.

The converters may also comprise one or more of the semiconductor devices which are mentioned under the "Background Art".

The introduction of such a single-winding/multiple-winding machine thus entails considerably lower investment costs and reduced requirements on space in relation to corresponding HVDC installations according to the state of the art. An HVDC installation according to the invention also permits the total efficiency of the installation to be increased. Also with regard to high-voltage variable-speed electric machine drives, the machine/converter concept according to the following description entails considerable advantages relative to the state of the art.

A rotating high-voltage single-winding/multiple-winding machine as an integral part of the present invention entails a considerably reduced thermal stress on the stator. Temporary overloads of the machine thus become less critical and it will be possible to drive the machine at overload for a longer period of time without running the risk of damage arising. This means considerable advantages for owners of power generating plants who are forced today, in case of operational disturbances, to rapidly switch to other equipment in order to ensure the delivery requirements laid down by regulations.

With a rotating high-voltage single-winding/multiple-winding machine as an integral part of the present invention, the maintenance costs can be significantly reduced because transformers, on-load tap changers, circuit breakers, filters, transmission lines, reactors, etc., do not have to be included in the system.

To increase the power of a rotating electric machine, it is known to attempt to increase the current in the ac coils. This has been achieved by optimizing the quantity of conducting material, that is, by close-packing of rectangular conductors in the rectangular rotor slots. The aim has been to handle the increase in temperature resulting from this by increasing the quantity of insulating material and using more temperature-resistant and hence more expensive insulating materials. The high temperature and field load on the insulation has also caused problems with the life of the insulation. In the relatively thick-walled insulating layers which are used for high-voltage equipment, for example impregnated layers of mica tape, partial discharges, PD, constitute a serious problem. When manufacturing these insulating layers, cavities, pores, and the like, will easily arise, in which internal corona discharges arise when the insulation is subjected to high electric field strengths. These corona discharges gradually degrade the material and may lead to electric breakdown through the insulation.

The great and essential difference between a rotating electric machine according to the state of the art and the embodiment according to the invention is that the magnetic circuit of the rotating high-voltage single-winding/multiple-winding machine comprises one or more windings, phase-shifted in space, of a threaded or wound cable with one or more solid insulated conductors with a semiconducting layer both at the conductor and the casing and, between the two semiconducting layers, a layer with a solid insulation. The outer semiconducting layer may be connected to ground potential.

If a converter connection according to Figures 1 and 2 is used, the solid insulating layer will be subjected to both ac and dc potentials. If, on the other hand, a converter connection according to Figure 3 is used, the solid layer will be subjected to ac potential only. The cable with which

the windings in a machine according to the invention is wound must thus be chosen with regard to the potential stress in question.

The present invention is based on the realization that, to be able to increase the power of a rotating electric machine in a technically and economically justifiable way, this must be achieved by ensuring that the insulation is not broken down by the phenomena described above. This can be achieved according to the invention by using as insulation layers made in such a way that the risk of cavities and pores is minimal, for example a solid extruded insulating layer of a suitable solid insulating material, such as thermoplastic resins or, alternatively, crosslinked materials such as XLPE or rubber, for example EP rubber or silicone rubber, also alternatively crosslinked. In addition, it is important that the insulation comprises an inner layer, surrounding the conductor, with semiconducting properties and that the insulation is also provided with at least one additional outer part, surrounding the solid insulating layer, with semiconducting properties. By using only a solid insulating layer which may be manufactured with a minimum of defects and, in addition, providing the solid layer with an inner and an outer semiconducting part, it can be ensured that the thermal and electric loads are reduced. At temperature gradients, the insulating part with the semiconducting layers will constitute a monolithic part and defects caused by different temperature expansion in the solid layer and the surrounding semiconducting layers do not arise. The electric load on the material decreases as a consequence of the fact that the semiconducting parts around the solid insulating layer will constitute equipotential surfaces and that the electric field in the solid insulating layer will thus be distributed uniformly over the thickness of the layer. The outer semiconducting layer may be connected to a ground potential. This means that, for such a cable, the outer casing of the winding in its entire length may be kept at ground potential.

The outer layer may also be cut off at suitable locations along the length of the conductor and each cut-off partial length may be directly connected to a chosen potential, ground potential. Around the outer semiconducting layer there may also be arranged other layers, casings and the like, such as a metal shield and a protective jacket.

Further knowledge gained in connection with the present invention is that increased current load leads to problems with voltage (E) field concentrations at the corners at a cross section of a coil and that this entails large local loads on the insulation there. Likewise, the magnetic (B) field in the tooth of the rotor will be concentrated at the corners. This means that magnetic saturation arises locally and that the magnetic core is not utilized in full and that the waveform of the generated voltage/current will be distorted. In addition, eddy losses caused by induced eddy currents in the conductors, which arise because of the geometry of the conductors in relation to the B field, will entail additional disadvantages at increasing current densities.

A further improvement of the invention is achieved by making the coils and the slots in which the coils are placed circular instead of rectangular. By making the coils circular, these will be surrounded by a constant B field without concentrations where magnetic saturation may arise. Also the E field in the coil will be distributed uniformly over the cross section and local loads on the insulation are considerably reduced. In addition, it is easier to place circular coils in slots in such a way that the number of coil sides per coil group may increase and an increase of the voltage may take place without the current in the conductors having to be increased. The reason is that the cooling of the conductors is facilitated by, on the one hand, a lower current density and hence lower temperature gradients across the insulation and, on the other hand, by the circular shape of the slots which entails a more uniform temperature distribution over a cross section. Additional improvements may also be achieved by composing the conductor from smaller parts, so-called strands. The strands may be insulated from each other and only a small number of strands may be left uninsulated and in contact with the inner semiconducting layer, to ensure that this is at the same potential as the conductor.

One further development of a conductor composed of strands is possible in that it is possible to insulate the strands with respect to each other in order thus to reduce the amount of eddy current losses in the conductor. One or a few of the strands may be left uninsulated to ensure that the semiconducting layer surrounding the conductor is at the same potential as the conductor.

One advantage with circular conductor shapes and the division into strands is that the harmonic currents are distributed very well. It may, therefore, be an advantage to have more strands in the conductor when harmonic currents may arise than when the current is more sinusoidal.

It is known that a high-voltage cable for transmission of electric energy is composed of conductors with extruded insulation with an inner and an outer semiconductor part. During transmission of electric energy, the starting-point has long been that the insulation should be free from defects.

Insulation of a conductor for a rotating single-winding/multiple-winding machine according to the invention may be applied in some other way than by means of extrusion, for example by spraying or the like. It is important, however, that the insulation should exhibit similar thermal properties through the whole cross section. The semiconducting layers may be supplied with the insulation in connection with the insulation being applied to the conductors.

Preferably, cables with a circular cross section are used. Among other things, to obtain a better packing density, cables with a different cross section may be used.

To build up a voltage in the rotating high-voltage single-winding/multiple-winding machine, the cable is disposed in several consecutive turns in slots in the magnetic core.

When the rotating high-voltage single-winding/multiple-winding machine is designed as a single-winding machine, it is normally utilized for six-pulse rectification. Nowadays, filter and module methods are available which cause the ripple on the rectified six-pulse voltage to be kept within acceptable limits.

A rotating high-voltage multiple-winding machine may, in principle, be designed with an optional number of winding systems and an optional number of phases. A preferred embodiment consists of a 2x3 phase system, electrically displaced relative to each other by 30 electrical degrees as

is required for a 12-pulse rectification. Other feasible combinations are a 2x2 phase system, a 4x3 phase system, etc.

A rotating high-voltage single-winding/multiple-winding machine according to the invention may operate within a wide frequency range. For large machines it may be a question of a few hundred Hz whereas for machines within the lower power range, frequencies of up to a few kHz may occur.

The winding can be designed as a multi-layer concentric cable winding to reduce the number of coil-end crossings. The cable may be made with tapered insulation to utilize the magnetic core in a better way, in which case the shape of the slots may be adapted to the tapered insulation of the winding.

A significant advantage with a rotating high-voltage single-winding/multiple-winding machine according to the invention is that the E field is near zero in the coil-end region outside the outer semiconductor and that with the outer casing at ground potential, the electric field need not be controlled. This means that no field concentrations can be obtained, neither within sheets, in coil-end regions, nor in the transition therebetween.

Devices according to the invention offer great possibilities of integration of parts included, such as semiconductor devices, cooling systems, grounding systems, etc. This will be described in greater detail in connection with the description of embodiments.

The present invention also relates to a method of manufacturing the magnetic circuit and, in particular, the winding. The method for manufacturing comprises disposing the winding in the slots by threading a cable into the openings in the slots in the magnetic core. Since the cable is flexible, it can be bent and this permits a cable length to be disposed in several turns in a coil. The coil ends will then consist of bending zones in the cables. The cable may also be joined in such a way that its properties remain constant over the cable length.

This method entails considerable simplifications compared with the state of the art. The so-called Roebel bars are not flexible but must be preformed into the desired shape.

Insulating windings and impregnation of the coils are also exceedingly complicated and expensive techniques when manufacturing rotating electric machines today.

A rotating high-voltage single-winding/multiple-winding machine according to the invention can also be designed as an air-gap-wound machine without magnetic material or as a machine with magnetic material in the back portion only.

To sum up, thus, a rotating high-voltage single-winding/multiple-winding machine with converters included in a device for speed control according to the invention means a considerable number of important advantages in relation to corresponding prior art machines. By high voltage are meant here voltages exceeding 10 kV and up to the voltage levels which occur for power networks. An important advantage is that a chosen potential, for example ground potential, has been consistently conducted along the whole winding, which means that the coil-end region can be made compact and that bracing means in the coil-end region can be applied at practically ground potential or any other chosen potential. Still another important advantage is that oil-based insulation and cooling systems disappear. This means that no sealing problems may arise and that the dielectric ring previously mentioned is not needed. One advantage is also that all forced cooling can be made at ground potential. A considerable space and weight saving from the installation point of view is obtained with a rotating high-voltage single-winding/multiple-winding machine according to the invention, since it replaces a previous installation design with two transformer stages. The very large and extensive bushings which are needed in the converter transformers to withstand the high dc potential to which bushings and windings are subjected are not needed with the machine concept according to the invention. The invention requires no superconducting rotor with the problems associated therewith, such as maintaining the temperature, encapsulation, and the like.

As is clear from the title of this invention, the invention comprises achieving a high-voltage variable-speed electric machine drive. For this alternative, the above-mentioned power conversion between AC and AC is suitably used, which means ac conversion/ac conversion with an arbitrary ratio between the frequency, amplitude, phase position, and phase number of the voltages. Such an arrangement functions as a kind of "ac transformer" which is able to reduce or increase the voltage, change frequencies and/or change phase numbers. The connection may have a pure AC/AC conversion, for example with a matrix converter, but may also be designed as a dc intermediate link.

The above-mentioned properties make the connection well suited to be included in an installation for high-voltage variable-speed electric machine operation together with the rotating high-voltage machine according to the invention. As will have been clear, according to conventional technique described above, the machine may be designed as a two-winding machine with feeding via two three-phase systems with phase-shifted voltages. A connection for such high-voltage electric machine operation is clear from Figure 4a.

Figure 4a shows an installation which is capable of serving both as a motor drive and as a generator drive. For economic and other technical/practical reasons, the currently maximum suitable voltage level of the machine windings amounts to 25-30 kV. As motor drive, power may be obtained from an ac network which, for example, may be a 132 kV network. The power conversion from alternating current with a fixed mains frequency to the variable voltage and frequency which are needed for speed control takes place in the example shown via an AC/AC conversion with a dc intermediate link, at a higher voltage level than 25-30 kV. The mains frequency is obtained via a transformer T3 with two secondary windings to achieve two voltage systems shifted 30 electrical degrees relative to each other. These two systems each feed an AC/DC converter, AC1 and AC2, respectively. The direct voltage from these is then converted via the DC/AC converters AC3 and AC4 to two three-phase voltages, shifted 30 electrical degrees relative to each other, with the voltage and the frequency which are needed to drive the motor M and the load, for example a pump, with the desired speed.

If the connection according to Figure 4a is to describe a generator drive, the generator GF is driven by a turbine, and via the AC/AC power conversion the windings of the transformer T3 may have such voltages that the ac network is fed with the desired voltage.

The connection according to Figure 4a has four parallel dc conductors which are physically extended in parallel over a short distance. The dc conductors carry equal currents but in two directions. In case of a long transmission distance, a connection according to Figure 4b is to prefer, since two dc connections are eliminated when the converters are series-connected. The connection according to Figure 4b causes the windings of the single-winding/multiple-winding machine to be subjected to dc potential.

The connection according to Figure 4c is an improvement of the connection in Figure 3 and connects the converters in parallel, which means that the windings of a single-winding/multiple-winding machine are not subjected to dc potential.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a conventional HVDC transmitter station.

Figure 2 shows an HVDC transmitter station with a so-called "Direct Connection".

Figure 3 shows a so-called interphase transformer connection.

Figures 4a, 4b and 4c show connections for high-voltage electric machine drive according to the invention.

Figure 5 shows the parts included in the current modified standard cable.

Figure 6 shows an embodiment of an axial end view of a sector/pole pitch of a magnetic circuit according to the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

One important condition for being able to manufacture a magnetic circuit in accordance with the summary of the invention is to use for the winding a cable with a semiconducting layer surrounding the conductor, which layer is surrounded by a layer of solid electric insulation and a semiconducting layer surrounding the solid layer. Such cables are available as standard cables for other power engineering fields of use. To be able to describe an embodiment, initially a short description of a standard cable will be made. The inner current-carrying conductor comprises a number of non-insulated strands. Around the strands there is a semiconducting inner casing. Around this semiconducting inner casing, there is an insulating layer of solid insulation. An example of such solid insulation is XLPE or, alternatively, so-called EP rubber such as silicone rubber, thermoplastic resins or crosslinked thermoplastic resins. This insulating layer is surrounded by an outer semiconducting layer which, in turn, is surrounded by a metal shield and a sheath. Such a cable will be referred to below as a power cable.

A rotating high-voltage single-winding/multiple-winding machine has as windings a cable, a preferred embodiment of which is shown in Figure 5. The cable 1 is described in the figure as comprising a current-carrying conductor 2 which comprises transposed both non-insulated and insulated strands. Electromechanically transposed, solid insulated strands are also possible. Around the conductor there is an inner semiconducting casing 3 which, in turn, is surrounded by a solid insulating layer 4. This layer is surrounded by an outer semiconducting layer 5. The cable used as a winding in the preferred embodiment has no metal shield and no external sheath. To avoid induced currents and losses associated therewith in the outer semiconductor, this may be cut off, preferably in the coil end, that is, somewhere in the transitions from the stack of sheets to the end windings. Each cut-off part is then connected to ground, whereby the outer semiconductor will be maintained at, or near, ground potential in the whole cable length. This means that, around the solid insulated winding at the coil ends, the contactable surfaces, and the surfaces which are dirty after some time of use, only have negligible potentials to ground, and they also cause negligible electric fields.

To optimize a rotating high-voltage single-winding/multiple-winding machine, the design of the magnetic circuit as regards the slots and the

teeth, respectively, is of decisive importance. In the embodiment with a threaded cable, the slots should be connected as close to the casing of the coil sides as possible. It is also desirable that the teeth at each radial level are as wide as possible. This is important to minimize the losses, the magnetization requirement, etc., of the machine.

With access to a conductor for the windings as the above-mentioned cable, there are great possibilities of being able to optimize the magnetic core from several points of view. In the following, a magnetic circuit in the stator of the rotating high-voltage single-winding/multiple-winding machine is referred to. Figure 6 shows an embodiment of an axial end view of a sector/pole pitch 6 of a machine according to the invention. The rotor with the rotor pole is designated 7. In conventional manner, the stator is composed of a laminated core of electric sheets successively composed of sector-shaped sheets. From a back portion 8 of the core, located at the radially outermost end, a number of teeth 9 extend radially inwards towards the rotor. Between the teeth there are a corresponding number of slots 10. The use of cables 11 according to the above among other things permits the depth of the slots for high-voltage machines to be made larger than what is possible according to the state of the art. The slots have a cross section tapering towards the rotor since the need of cable insulation becomes lower for each winding layer towards the rotor. As is clear from the figure, the slot substantially consists of a circular cross section 12 around each layer of the winding with narrower waist portions 13 between the layers. With some justification, such a slot cross section may be referred to as a "cycle chain slot". Since in such a high-voltage machine, a relatively large number of layers will be needed, and the supply of relevant cable dimensions as far as insulation and outer semiconductors are concerned is limited, it may in practice be difficult to achieve a desired continuous tapering of the cable insulation and the stator slot, respectively. In the embodiment shown in Figure 6, cables with three different dimensions of the cable insulation are used, arranged in three correspondingly dimensioned sections 14, 15 and 16, that is, in practice a modified cycle chain slot will be obtained. The figure also shows that the stator tooth can be shaped with a practically constant radial width along the depth of the whole slot.

In an alternative embodiment, the cable which is used as a winding may be a conventional power cable as the one described above. The grounding of the outer semiconducting shield then takes place by stripping the metal shield and the sheath of the cable at suitable locations.

The scope of the invention accommodates a large number of alternative embodiments, depending on the available cable dimensions as far as insulation and the outer semiconductor layer etc. are concerned. Also embodiments with so-called cycle chain slots can be modified in excess of what has been described here.

As mentioned above, the magnetic circuit may be located in the stator and/or the rotor of the rotating high-voltage single-winding/multiple-winding machine. However, the design of the magnetic circuit will largely correspond to the above description independently of whether the magnetic circuit is located in the stator and/or the rotor. As mentioned in the introductory part of the description, the machine may be designed as an air-gap-wound machine without magnetic material or with magnetic material in the back portion only.

As windings, windings are preferably used which may be described as multilayer, concentric cable windings. Such windings mean that the number of crossings at the coil ends has been minimized by placing all the coils within the same group radially outside one another. This also permits a simpler method for the manufacture and the threading of the stator winding in the different slots. If the machine is made as a machine with salient poles, the winding/windings will be wound around the salient poles.

In an alternative embodiment of the rotating high-voltage single-winding/multiple-winding machine, the cable may be wound around salient poles in a way which resembles an embodiment of a high-voltage transformer according to Swedish patent application 9700335-4.

In the examples of embodiments of single-winding/multiple-winding machines illustrated here, embodiments with a radial flux and axial winding currents have been used. Single-winding/multiple-winding machines with an axial air-gap flux and radial winding currents may also be

designed in a way similar to that of low-voltage machines using present-day technique.

In one embodiment of an installation according to the invention, the semiconductor devices may constitute an integral part of the high-voltage single-winding/multiple-winding machine.

The single-winding/multiple-winding machine and the semiconductor devices may have a common cooling system.

The single-winding/multiple-winding machine and the semiconductor devices shall have the same, and common, ground connection.

CLAIMS

1. An installation comprising a rotating high-voltage single-winding/multiple-winding machine and a converter, **characterized** in that a mechanical torque is converted into direct current and direct voltage via the converter without intermediate transformers and/or reactors.

2. An installation according to claim 1, **characterized** in that the converter comprises semiconductor devices which are connected and function as an AC/DC converter.

3. An installation comprising a rotating high-voltage single-winding/multiple-winding machine and a converter, **characterized** in that direct current and direct voltage are converted via the converter into a mechanical torque without intermediate transformers and/or reactors.

4. An installation according to claim 3, **characterized** in that the converter comprises semiconductor devices which are connected and function as a DC/AC converter.

5. An installation according to claims 1 and 2, **characterized** in that to the AC/DC rectifier there is connected a DC/AC inverter with direct connection to an ac network without intermediate transformers and/or reactors.

6. An installation according to claims 3 and 4, **characterized** in that to the dc side of the DC/AC inverter there is connected a DC/AC rectifier with direct connection to an ac network without intermediate transformers and/or reactors.

7. An installation according to claims 2 and 4, **characterized** in that to the semiconductor devices may consist of thyristors, diodes, triacs, gate turn-off thyristors (GTO), bipolar transistors (BJT), PWM transistors, MOSFET, insulated gate bipolar transistors (IGBT), static induction transistors (SIT), static induction thyristors (SITH), MOS-controlled thyristors (MCT) and similar components with semiconductor properties.

8. An installation according to claims 1, 2, 3 and 4, **characterized** in that the converters constitute an integral part of the rotating high-voltage single-winding/multiple-winding machine.

9. An installation according to claims 1, 2 and 5, **characterized** in that the converters constitute an integral part of the rotating high-voltage single-winding/multiple-winding machine.

10. An installation according to claims 1, 2 and 6, **characterized** in that the converters constitute an integral part of the rotating high-voltage single-winding/multiple-winding machine.

11. An installation according to claims 1, 2 and 5, **characterized** in that the rotating high-voltage single-winding/multiple-winding machine and the semiconductor devices have a common cooling system.

12. An installation according to claims 1, 2 and 6, **characterized** in that the rotating high-voltage single-winding/multiple-winding machine and the semiconductor devices have a common cooling system.

13. An installation according to claims 1, 2 and 5, **characterized** in that the rotating high-voltage single-winding/multiple-winding machine and the semiconductor devices have the same and common ground connection.

14. An installation according to claims 1, 2 and 6, **characterized** in that the rotating high-voltage single-winding/multiple-winding machine and the semiconductor devices have the same and common ground connection.

15. An installation according to claims 1 and 3 and wherein the rotating high-voltage single-winding/multiple-winding machine comprises a magnetic circuit with one or more magnetic cores and one or more windings phase-shifted in space, **characterized** in that the windings comprise one or more current-carrying conductors (2), that around each conductor there is arranged a first layer (3) with semiconducting properties, that around the first layer there is arranged a solid insulating layer (4), and that around the insulating layer there is arranged a second layer (5) with semiconducting properties.

16. A rotating high-voltage single-winding/multiple-winding machine according to claim 15, **characterized** in that the first layer (3) is at substantially the same potential as the conductor.

17. A rotating high-voltage single-winding/multiple-winding machine according to claim 15, **characterized** in that the second layer (5) is arranged in such a way that it constitutes an equipotential surface surrounding the conductor/conductors.

18. A rotating high-voltage single-winding/multiple-winding machine according to claim 15, **characterized** in that the second layer (5) is connected to ground potential.

19. A rotating high-voltage single-winding/multiple-winding machine according to claim 15, 16, 17 or 18, **characterized** in that, for the winding, all the semiconducting layers and insulating layers exhibit similar thermal properties, such that, upon a thermal movement in the winding, no defects, cracks, or the like, occur in the insulating parts.

20. A rotating high-voltage single-winding/multiple-winding machine according to claim 15, **characterized** in that the current-carrying conductor comprises a number of strands, whereby only a small number of the strands are non-insulated from each other.

21. A rotating high-voltage single-winding/multiple-winding machine wherein the magnetic circuit comprises a magnetic core and one or more windings phase-shifted in space, **characterized** in that the windings comprise a cable including one or more current carrying conductors (2), that each conductor comprises a number of strands, that around each conductor there is arranged an inner semiconducting layer (3), around which there is arranged an insulating layer (4) of solid insulation, around which there is arranged an outer semiconducting layer (5).

22. A rotating high-voltage single-winding/multiple-winding machine with a magnetic circuit according to claim 21, **characterized** in that the cable also comprises a metal shield and/or a protective layer.

23. A rotating high-voltage single-winding/multiple-winding machine according to claim 21, **characterized** in that the magnetic circuit is arranged in the stator and/or the rotor of the rotating electric machine.

24. A rotating high-voltage single-winding/multiple-winding machine according to claim 21, **characterized** in that the outer semiconducting layer (5) is cut off into a number of parts which are separately connected to ground potential.

25. A rotating high-voltage single-winding/multiple-winding machine according to claim 21, 22, 23 or 24, **characterized** in that with connection of the outer semiconducting layer to ground potential, the electric field of the machine outside the semiconducting layer both in the slots and in the coil-end region will be near zero.

26. A rotating high-voltage single-winding/multiple-winding machine according to claims 21 and 22, **characterized** in that, when the cable comprises several conductors, these are transposed.

27. A rotating high-voltage single-winding/multiple-winding machine with a magnetic circuit according to claim 21, **characterized** in that the current-carrying conductor/conductors (2) comprise both non-insulated and insulated wires, stranded into a number of layers.

28. A rotating high-voltage single-winding/multiple-winding machine with a magnetic circuit according to claim 21, **characterized** in that the current-carrying conductor/conductors (2) comprise both non-insulated and insulated strands, transposed into a number of layers.

29. A rotating high-voltage single-winding/multiple-winding machine with a magnetic circuit according to claim 21, **characterized** in that the slots (10) are formed as a number of cylindrical openings (12), extending axially and radially outside one another, with a substantially circular cross section separated by a narrower waist portion (13) between the cylindrical openings.

30. A rotating high-voltage single-winding/multiple-winding machine with a magnetic circuit according to claims 21 and 29, **characterized** in that

the substantially circular cross section of the cylindrical openings (12) of the slots, counting from a back portion (8) of the laminated core, is designed with a continuously decreasing radius.

31. A rotating high-voltage single-winding/multiple-winding machine with a magnetic circuit according to claims 21 and 29, **characterized** in that the substantially circular cross section of the cylindrical openings (12) of the slots, counting from a back portion (8) of the laminated core, is designed with a discontinuously decreasing radius.

32. A rotating high-voltage single-winding/multiple-winding machine wherein the magnetic circuit comprises a magnetic core and one or more windings, phase-shifted in space, **characterized** in that the magnetic core is formed with salient poles.

33. A rotating high-voltage single-winding/multiple-winding machine, **characterized** in that it is air-gap-wound.

34. A rotating high-voltage single-winding/multiple-winding machine, **characterized** in that the air-gap flux is radial.

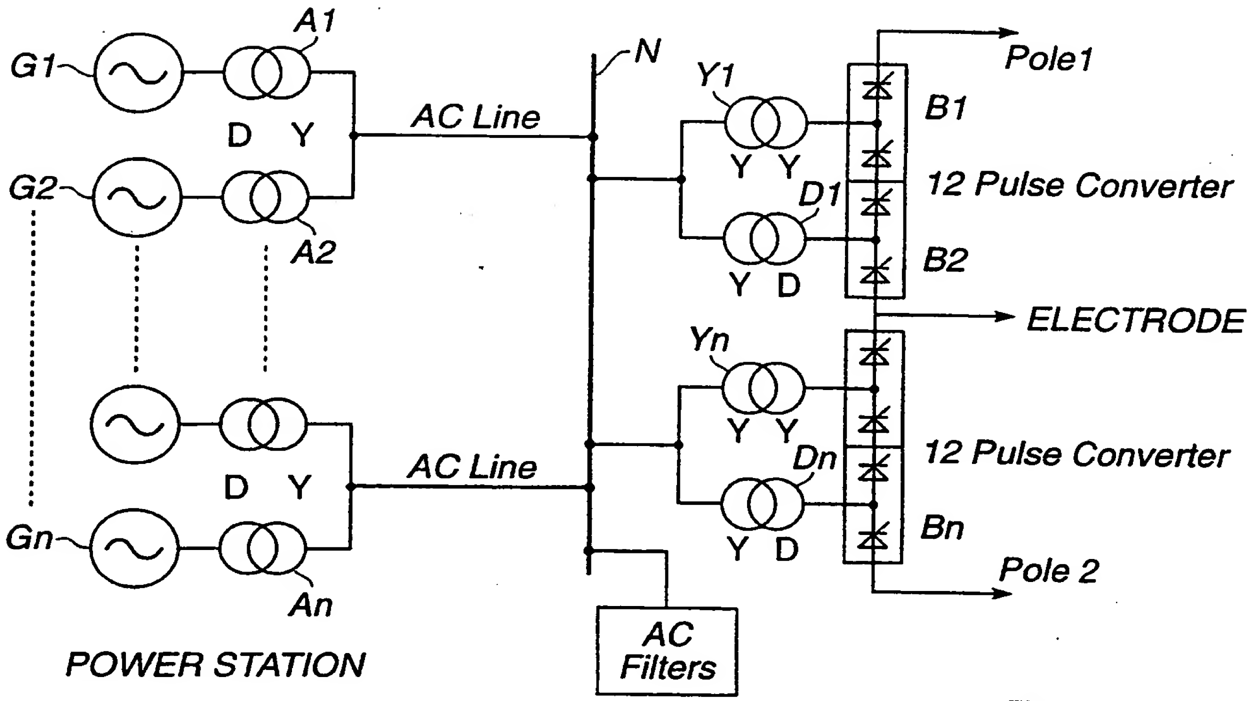
35. A rotating high-voltage single-winding/multiple-winding machine, **characterized** in that the air-gap flux is axial.

36. A method for manufacturing a rotating high-voltage single-winding/multiple-winding machine comprising a magnetic circuit comprising a magnetic core comprising slots, channels or the like, whereby these slots etc. have at least one opening, accessible from the outside of the magnetic core, and a winding, **characterized** in that the winding is flexible and is threaded into the opening.

37. A method for manufacturing a magnetic circuit for a rotating high-voltage single-winding/multiple-winding machine, wherein the magnetic circuit is arranged in the stator and/or rotor of the rotating electric machine, which magnetic circuit comprises a magnetic core (8) with slots (10) for two or more windings (1), phase-shifted in space, and wherein the slots are formed as cylindrical openings (12), extending axially and radially outside one another, with a substantially circular cross

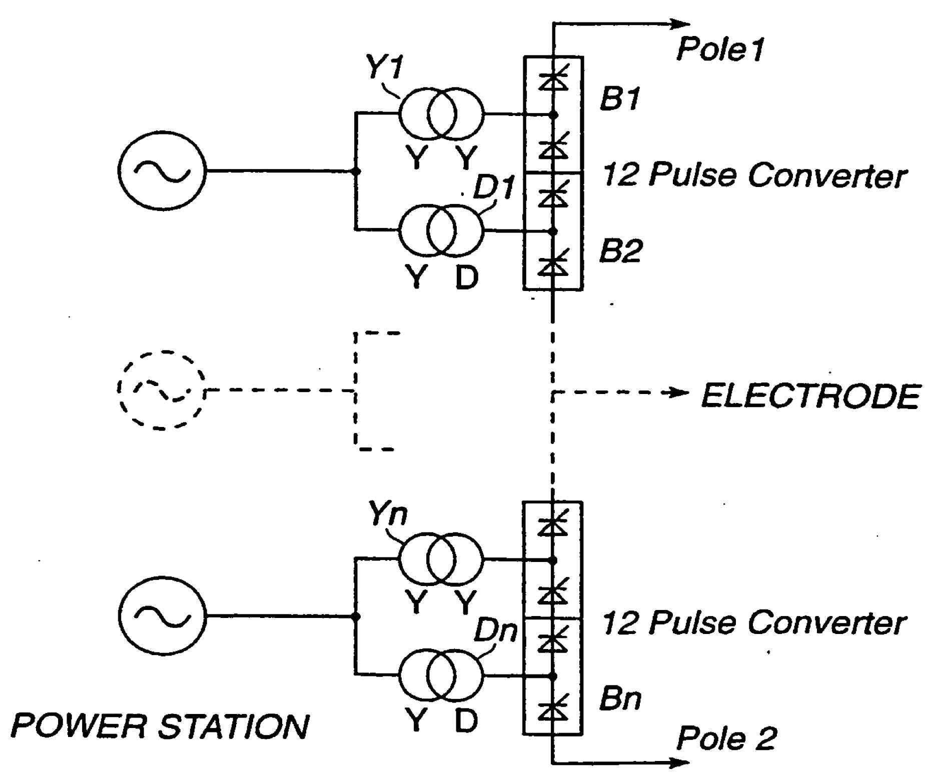
section, the method being **characterized** in that the winding comprises a cable which is threaded into the cylindrical openings.

38. A method for manufacturing a magnetic circuit for a rotating high-voltage single-winding/multiple-winding machine, wherein the magnetic circuit is arranged in the stator and/or rotor of the rotating electric machine and is formed as salient poles, the method being **characterized** in that the winding comprises a cable which is wound around the salient poles.



G1
A1
D Y
G2
A2
AC Line
N
Y1
Y Y
D1
Y D
Pole1
B1
12 Pulse Converter
B2
ELECTRODE
Yn
Y Y
Dn
Y D
12 Pulse Converter
Bn
Pole 2
D Y
AC Line
Gn
An
AC Filters
POWER STATION

Fig. 1



Pole1
Y1
B1
Y Y
12 Pulse Converter
D1
B2
Y D
ELECTRODE
Yn
Y Y
12 Pulse Converter
Dn
Bn
POWER STATION
Y D
Pole 2

Fig. 2

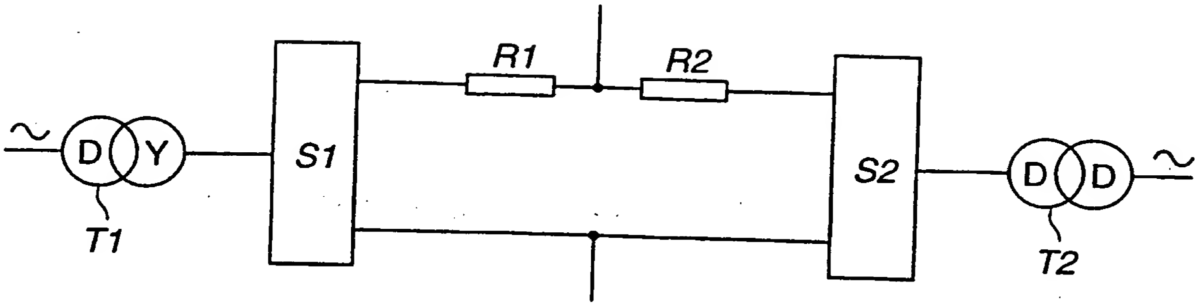


Fig. 3

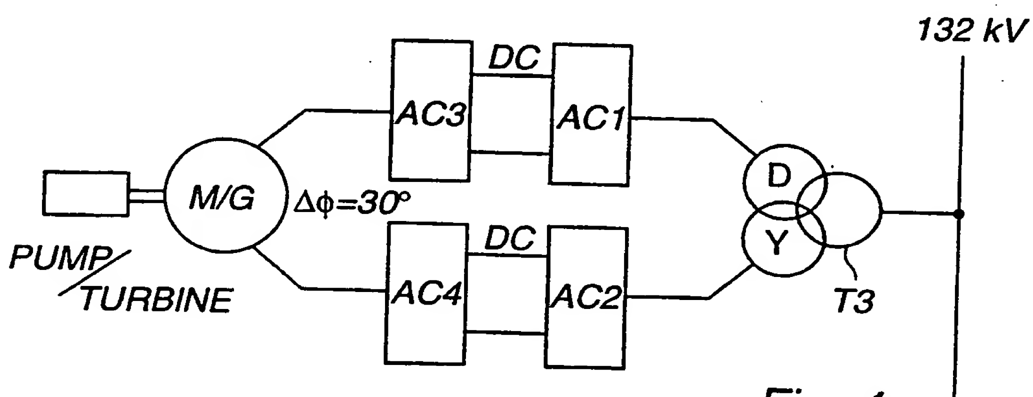


Fig. 4a

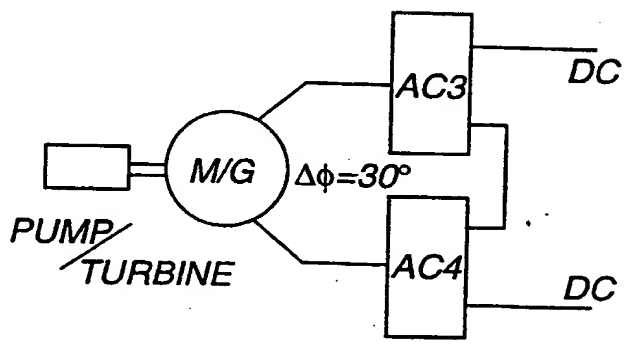


Fig. 4b

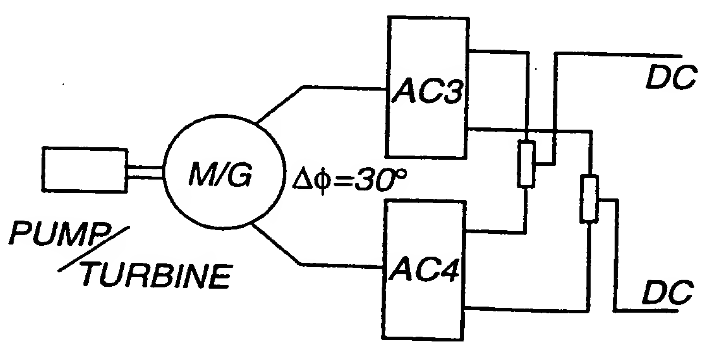


Fig. 4c

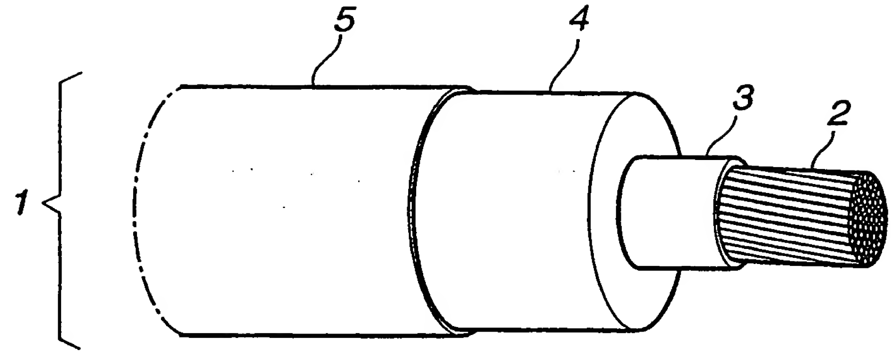


Fig. 5

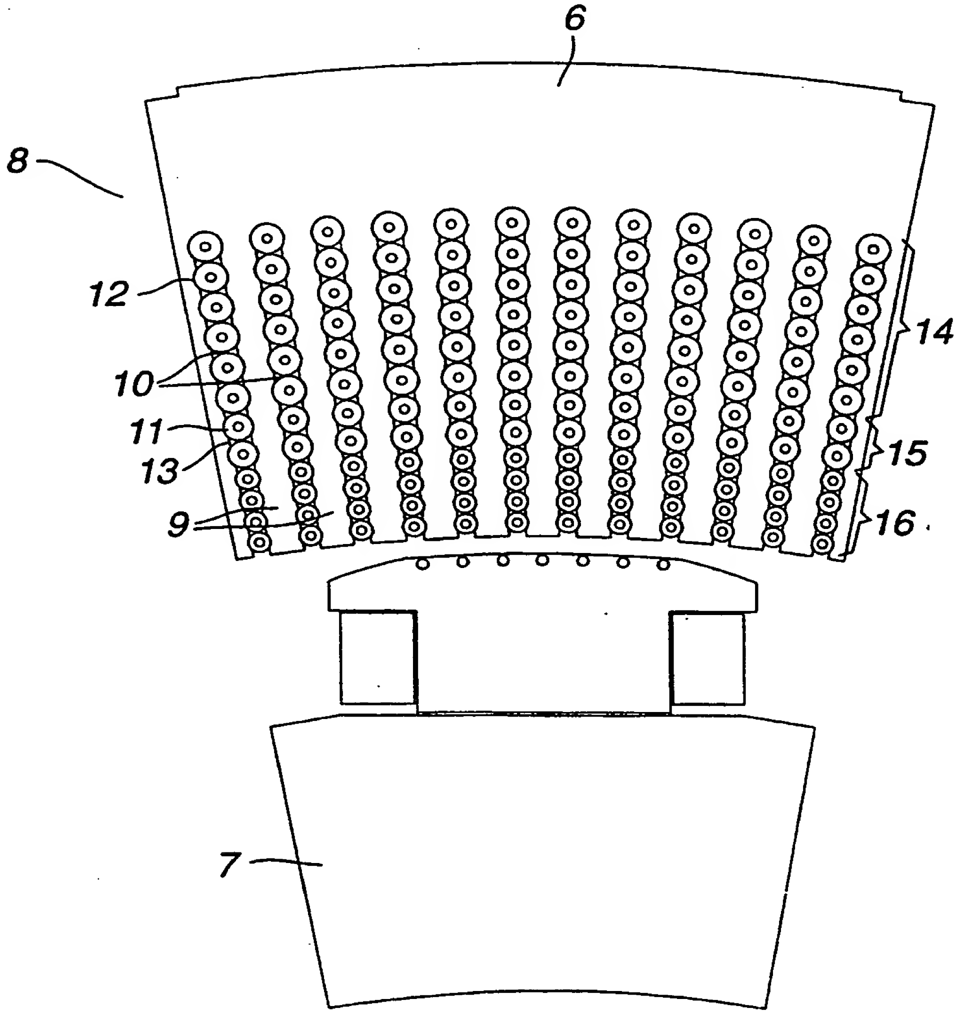


Fig. 6